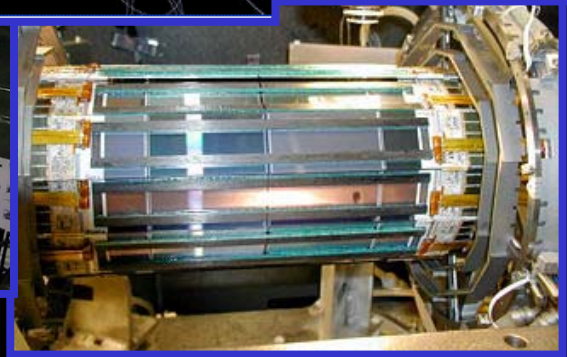
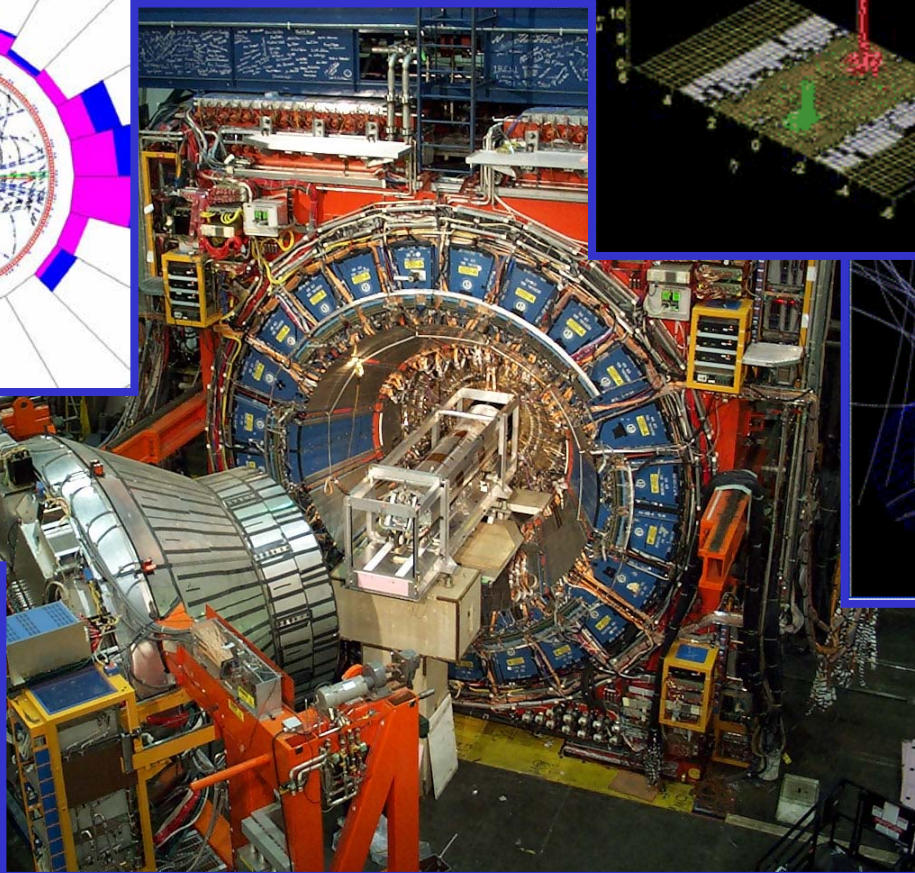
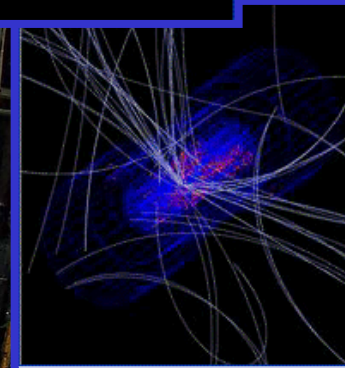
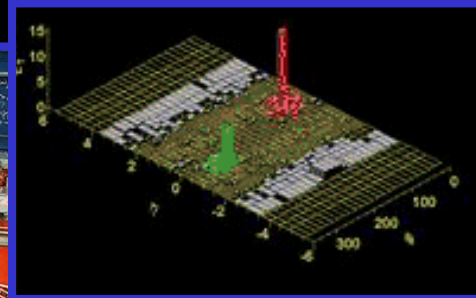
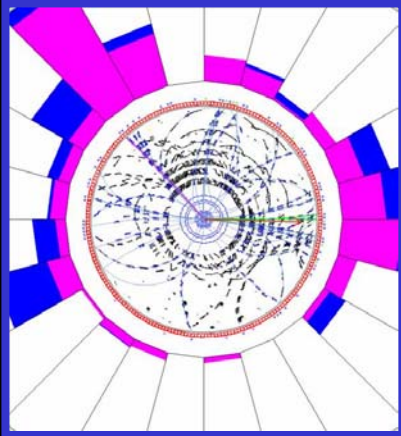


CDF Hot Topics

FPCP 2006
Vancouver, BC
April 9th – 12th 2006



Diego Tonelli
I.N.F.N. Pisa

Outline

Caveat: this will NOT be a wide overview of the latest CDF results.

Focus on selected topics (charm-less B decays in two charged particles) which will be described in detail.

Analysis of such modes provides CDF with a physics program competitive (B^0 modes), and complementary (B_s^0 modes) to B -factories. Well suited to illustrate the methods used in flavor physics at CDF.

- ✓ Tevatron and CDF;
- ✓ HF physics at hadron colliders;
- ✓ Trigger on displaced tracks;
- ✓ CP asymmetry in $B^0 \rightarrow K^+ \pi^-$ decays;
- ✓ $\Delta\Gamma_s/\Gamma_s$ in $B_s^0 \rightarrow K^+ K^-$ decays;
- ✓ search for FCNC $B_{(s)}^0 \rightarrow \mu^+ \mu^-$ decays.

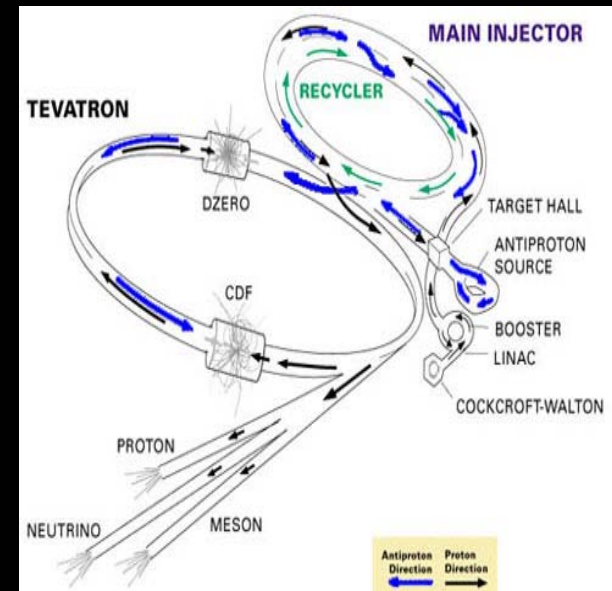
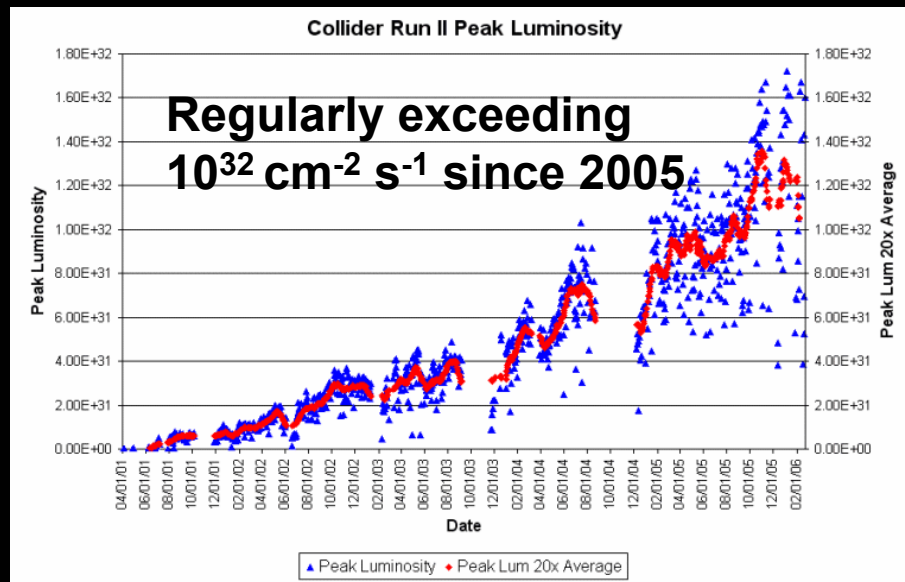
The Tevatron $\bar{p}p$ collider

Superconducting proton-synchrotron.....: 36 (*proton*) \times 36 (*antiproton*) bunches
a collision every 396 ns at $\sqrt{s} = 1.96$ TeV

of interactions per bunch-crossing.....: $\langle N \rangle_{\text{poisson}} = 2$ (at $10^{32} \text{ cm}^{-2}\text{s}^{-1}$)

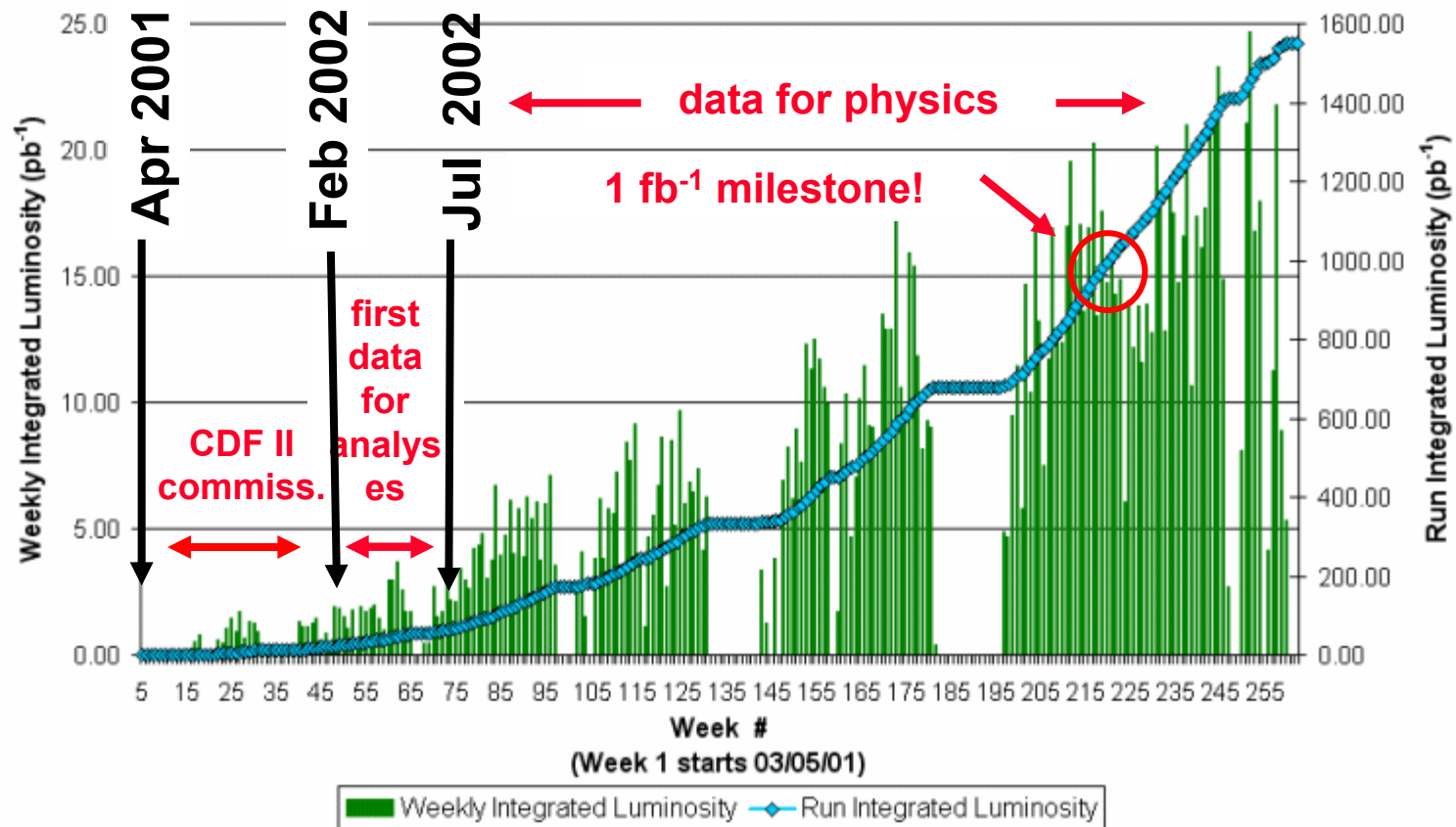
Luminous region size.....: 30 cm (beam axis) \times 30 μm (transverse)
need long Si-vertex small wrt $c\tau(B) \sim 450 \mu\text{m}$

Luminosity.....: record peak is $1.82 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
typically $18 \text{ pb}^{-1} / \text{week on tape}$



Luminosity

$\sim 1600 \text{ pb}^{-1}$ on tape ($\sim 1000 \text{ pb}^{-1}$ with silicon)



Stable data taking efficiency: $> 85\%$. Results here use $360 - 800 \text{ pb}^{-1}$

The CDF II detector

Some resolutions
 $p_T \sim 0.15\%$ p_T (c/GeV)
 J/ψ mass ~ 14 MeV/c²
 EM $E \sim 16\%/\sqrt{E}$
 Had $E \sim 80\%/\sqrt{E}$
 $d_0 \sim 40$ μm
 (includes beam spot)

1.4 T magnetic field
Lever arm 132 cm

132 ns front end
 chamber tracks at L1
 silicon tracks at L2
 25000 / 300 / 100 Hz
 with dead time $< 5\%$

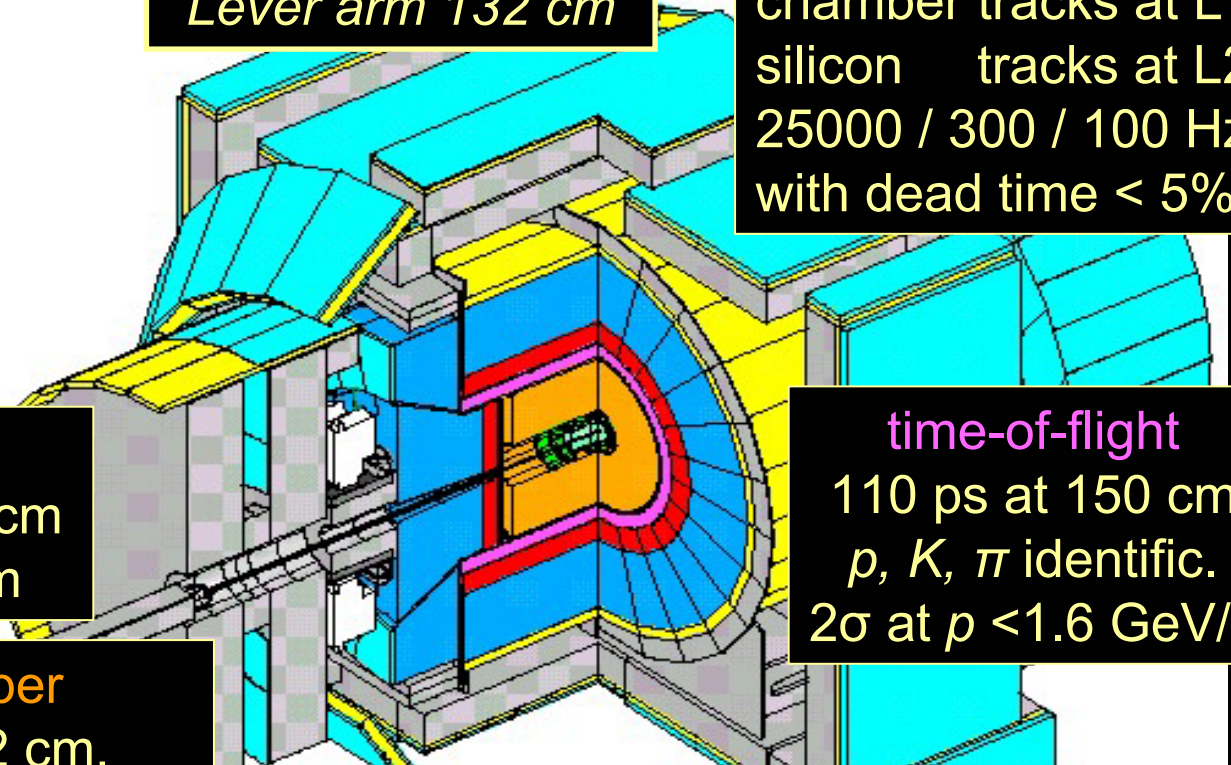
7 to 8 silicon layers
 $1.6 < r < 28$ cm, $|z| < 45$ cm
 $|\eta| \leq 2.0$ $\sigma(\text{hit}) \sim 15$ μm

96 layer drift chamber
 $|\eta| \leq 1.0$ $44 < r < 132$ cm,
 $|z| < 155$ cm 30k channels,
 $\sigma(\text{hit}) \sim 140$ μm
 dE/dx for p , K , π , e identification

time-of-flight
 110 ps at 150 cm
 p , K , π identific.
 2σ at $p < 1.6$ GeV/c

scintillator and tile/fiber
 sampling calorimetry
 $|\eta| < 3.64$

μ coverage
 $|\eta| \leq 1.5$
 84% in ϕ



Heavy Flavor physics at the Tevatron

The Good

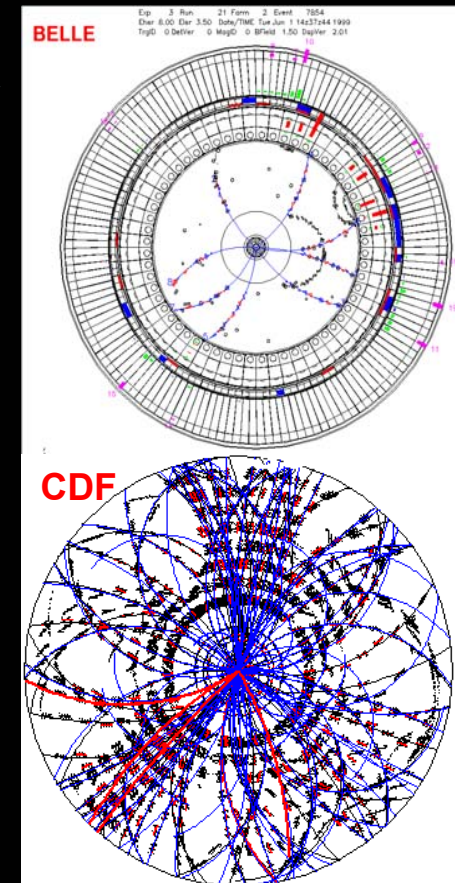
$p\bar{p} \rightarrow b\bar{b}$ x-section is $O(10^5)$ larger than $e^+e^- \rightarrow b\bar{b}$ at $\Upsilon(4S)$ or Z^0 . Copious samples of all b -hadrons, B^+ , B^0 , B_s^0 , B_c , Λ_b , Ξ_b etc, via strong interaction.

The Bad

Total inelastic x-section $\times 10^3$ larger than $\sigma(b\bar{b})$ and $p_T(B) \sim 5$ GeV/c: need high bckg rejection. Incoherent production and low ($\sim 10\%$) acceptance for “other B ”: hard flavor-tagging.

...and The Ugly

multiple interactions/event and debris from interacting \bar{p} and p : messy environments with large combinatorics. Challenging reduction from 1.7 MHz collision-rate, to ~ 100 Hz tape-writing.



Need highly selective trigger

Heavy flavor signature

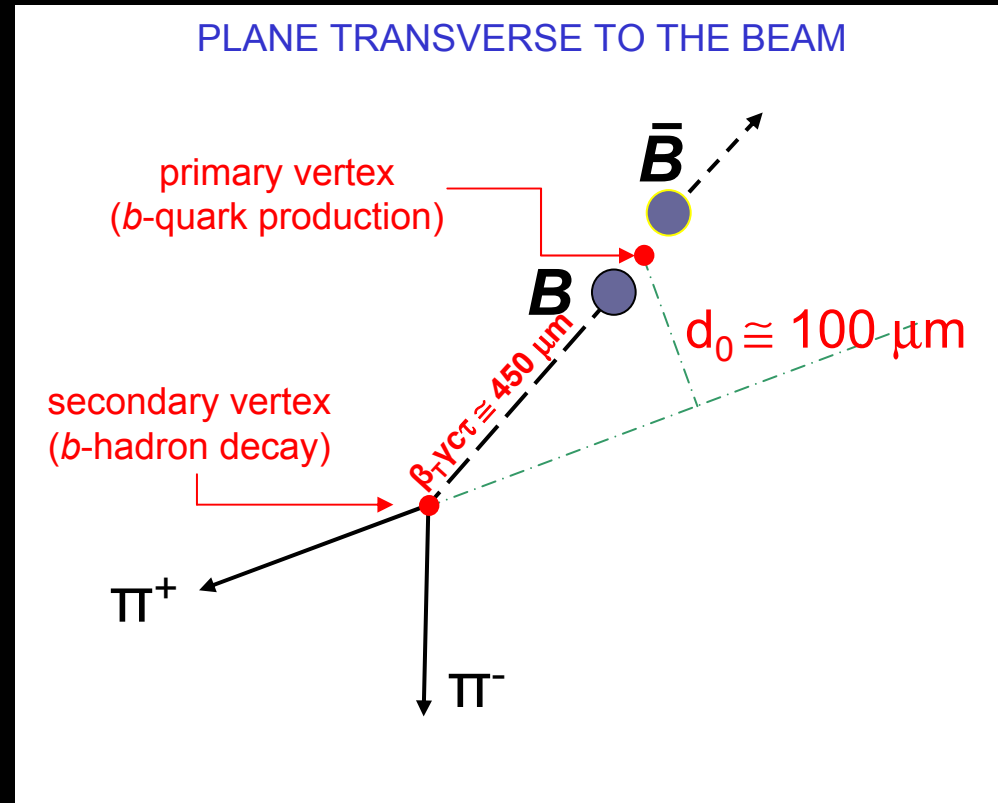
“Long” (~ 1.5 ps) lifetime of b -hadrons: a powerful signature against light-quark background. Before decaying, sufficiently boosted b -hadrons fly a distance resolvable with vertex detectors.

In Run I, CDF exploited this in offline analyses.

In Run II, we exploit it at trigger level. An experimental challenge that requires:

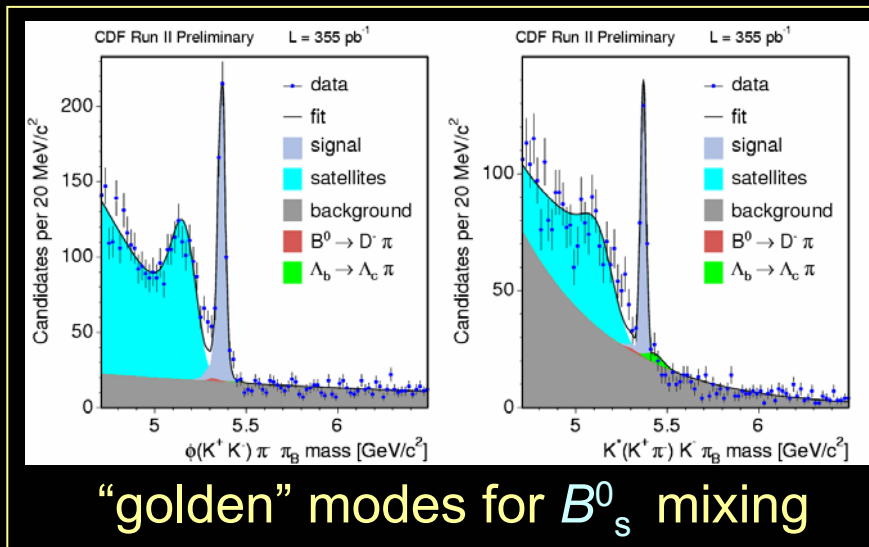
- (1) high resolution vertex detector (silicon)
- (2) read out silicon r- ϕ side (212,000 channels);
- (3) do pattern recognition and track fitting in silicon.

} within 25 μ s.



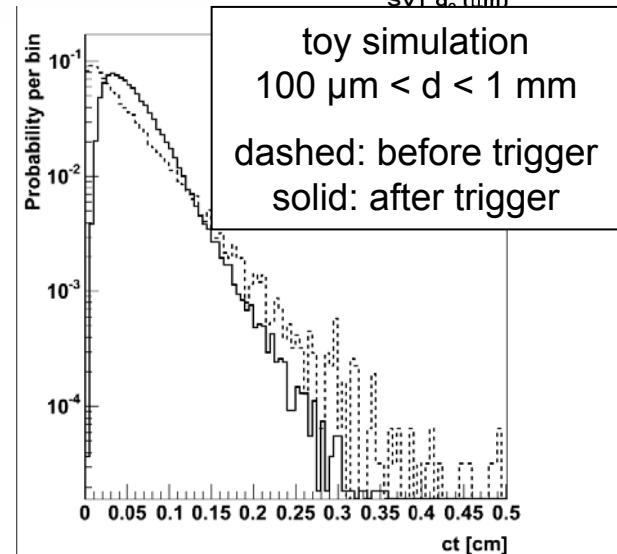
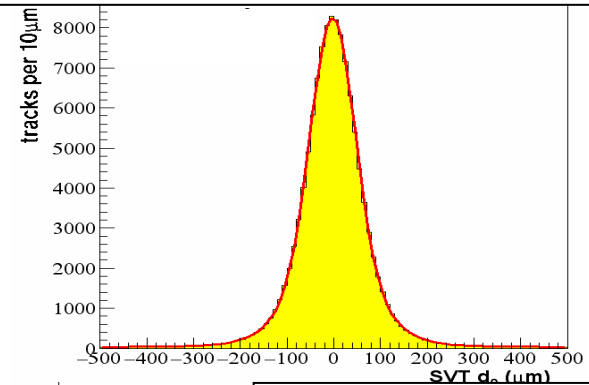
Displaced track trigger: pros and cons

Collection of very high-purity samples of hadronic B (and D) decays.



price to pay: trigger-bias distorts the proper-time distributions. Introduce complexity in lifetime-based analyses,more later...

impact parameter resolution
 $48 \text{ } \mu\text{m} = 35 \text{ [SVT]} \oplus 33 \text{ [beam-spot size]}$



Triggering heavy flavors

Traditional B -trigger at hadronic collider: look for one ($B \rightarrow l\nu X$) or two leptons ($B \rightarrow J/\psi X$) exploiting clear signature and $\sim 20\%$ of total width.

For the first time, trigger HF without leptons: rare hadronic B decays.

conventional

di-muon

$B \rightarrow \text{charmonium}$

$B \rightarrow \mu\mu$

two muons with:

$p_T > 1.5 \text{ GeV} \quad |\eta| < 1$

partially new approach

electron or μ and displaced track

$B \rightarrow l\nu X$

electron (or μ) with:

$p_T > 4 \text{ (or } 1.5) \text{ GeV} \quad |\eta| < 1$

and one track with:

$p_T > 2.0 \text{ GeV} \quad d_0 > 120 \mu\text{m}$

new approach

two displaced tracks

$B \rightarrow hh$

two tracks with:

$p_T > 2.0 \text{ GeV}$

$\Sigma p_T > 5.5 \text{ GeV}$

$d_0 > 100 \mu\text{m}$

CP Asymmetry
in $B^0 \rightarrow K^+\pi^-$ decays
and
 $B_s^0 \rightarrow K^+K^-$ lifetime

Motivation

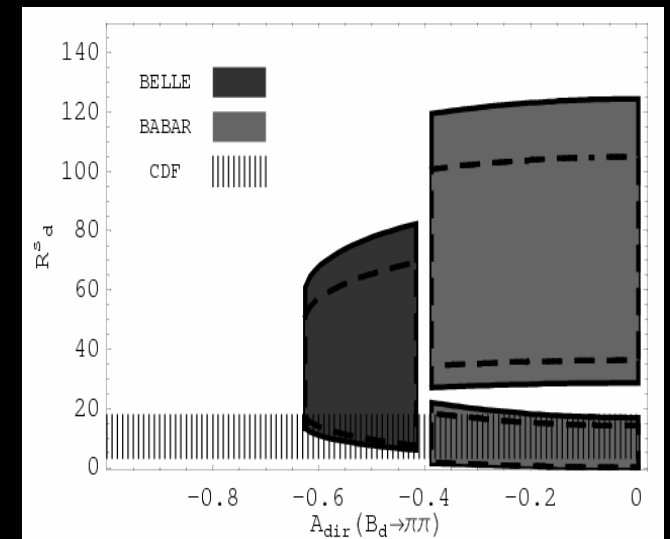
Interpretation of B results often plagued by uncertainties from non-perturbative QCD. Symmetries allows partial cancellation of the unknowns.

Joint study of B^0 and B_s^0 2-body decays into charged kaons and pions (KK , $\pi\pi$ and $K\pi$) plays a key role: related by subgroups of SU(3) symmetry.

Until the beginning of the planned $Y(5S)$ run at Belle, only CDF has simultaneous access to both $B^0/B_s^0 \rightarrow h^+h^-$ decays thus exploiting an original physics program complementary to B -factories.

BR can constrain theory: compare CDF measurements with allowed regions in spaces of $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ observables ($Y(4S)$ and theory) provides
a probe for both γ and NP

(Fleischer and Matias PRD66: 054009,2002
- London and Matias PRD70:031502, 2004.)



Motivation

These modes include $B^0 \rightarrow K^+\pi^-$, where direct CP asymmetry was observed for the first time in the B sector (B -factories).

Large ($\sim 10\%$) effect established, but still many things to understand, e.g. asymmetry in B^0 not compatible with B^+ as expected.

(Gronau and Rosner, Phys.Rev.D71:074019, 2005).

Additional experimental input is helpful: copious yields at Tevatron make CDF a major player in the direct-CPV game.

Compare rates and asymmetries of $B^0 \rightarrow K^+\pi^-$ and $B_s^0 \rightarrow K^-\pi^+$ - unique to CDF - to probe NP with no need for assumptions, just basing on SM.

(Lipkin, Phys.Lett.B621:126, 2005)

From lifetime of $B_s^0 \rightarrow K^+K^-$ (unique to CDF), information on the relative width-difference $\Delta\Gamma_s/\Gamma_s$. Supplements $B_s^0 \rightarrow J/\psi\phi$ for upper bounds on B_s^0 mixing frequency. Can be strongly affected by new, CP-violating physics.

Trigger confirmation

TRIGGER REQUIREMENTS

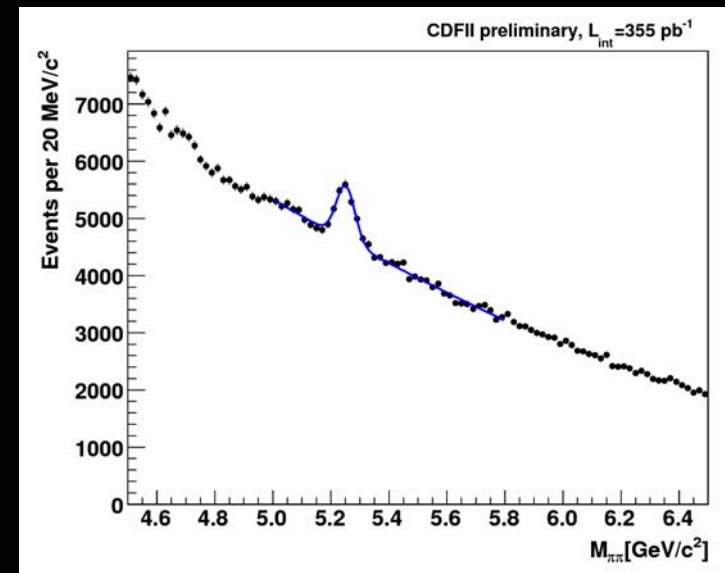
Two oppositely-charged tracks
(i.e. B candidate) from a long-lived decay:

- ✓ track's impact parameter $> 100 \mu\text{m}$;
- ✓ B transverse decay length $> 200 \mu\text{m}$;

B candidate pointing back to primary vertex:

- ✓ impact parameter of the $B < 140 \mu\text{m}$;
- reject light-quark background from jets:
- ✓ transverse opening angle $[20^\circ, 135^\circ]$;
- ✓ p_{T1} and $p_{T2} > 2 \text{ GeV}$;
- ✓ $p_{T1} + p_{T2} > 5.5 \text{ GeV}$.

offline confirmation of trigger cuts on track pairs fit to a common vertex:



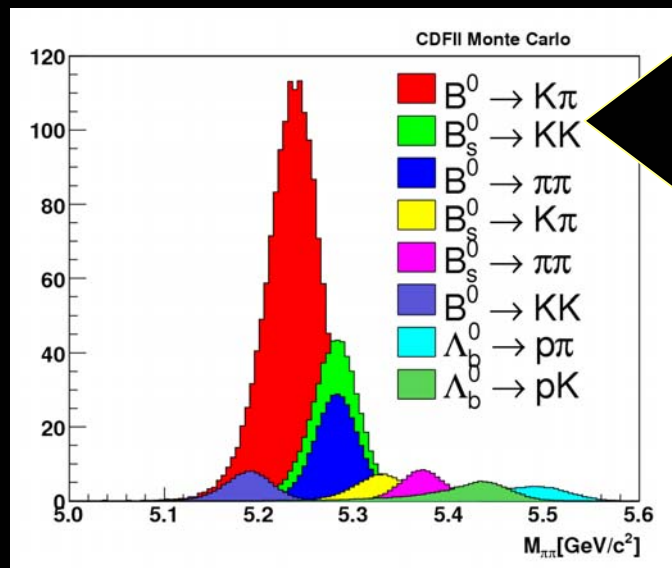
a bump of ~ 3850 events
with $S/B \approx 0.2$ (at peak)
in $\pi\pi$ -invariant mass

“optimized” cut optimization

Optimize cuts by minimizing the average expected statistical resolution on A_{CP} . Its expression in terms of S and B is determined from actual resolutions observed in analysis of toy-MC samples

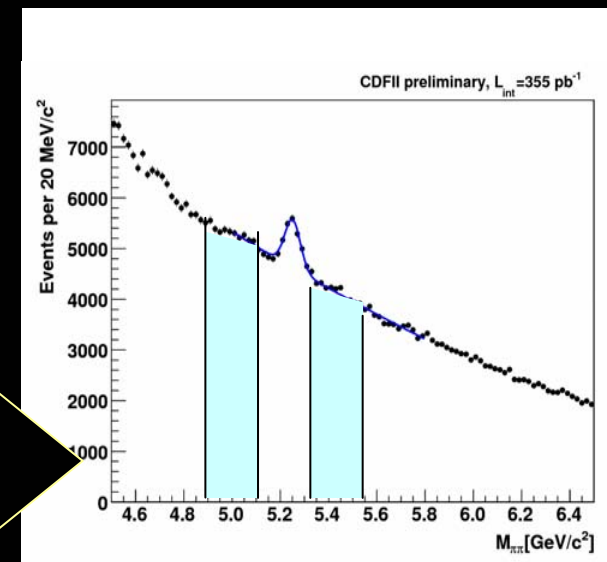
Gain $\sim 10\%$ improvement in resolution *versus* standard $S/\sqrt{(S+B)}$

Unbiased cut optimization: for any combination of cuts, evaluate the above score function; optimal cuts are found when the function reach its maximum.



signal yield S is derived from MC simulation

background B from data (mass sidebands)

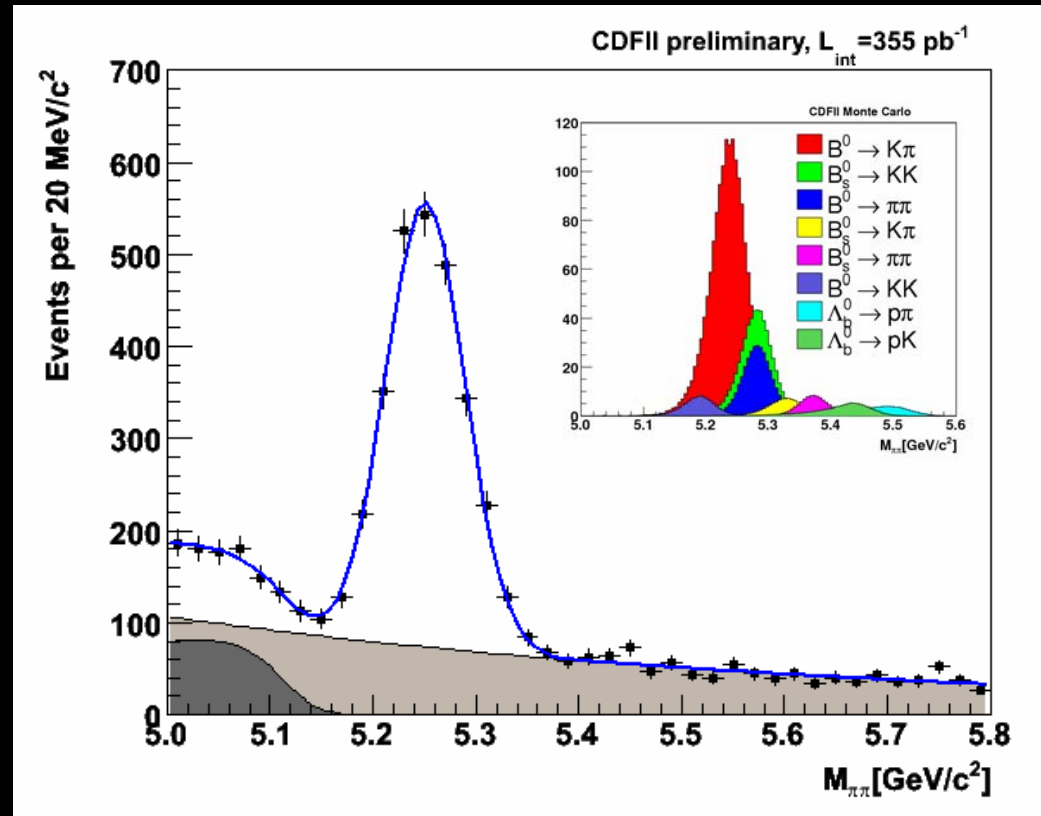
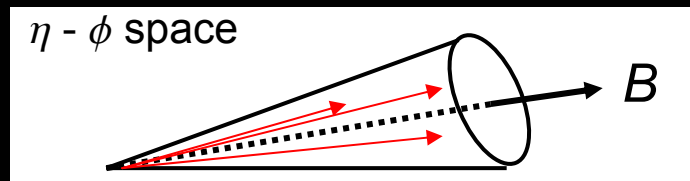


Signal extraction

Signal yield: ~ 2300 events
 $S/B \approx 6.5$ (peak value)

$\sim 1.7\times$ reduction in signal yield
 $\sim 50\times$ reduction in background

Crucial isolation:
 fraction of p_T carried by the B
 after fragmentation. Rejects
 18% of sig. and $\sim 4\times$ of bckg



Despite excellent mass resolution, modes overlap into an unresolved mass peak. No event-by-event PID.

Hence, fit signal composition with a Likelihood that combines information from kinematics (masses and momenta) *and* particle ID (dE/dx).

Peak composition handle 1: kinematics

Exploit the (small) kinematic differences among different modes:

4 values of the invariant mass of the track pair, resulting from all possible mass assignments ($K\pi$, πK , KK , $\pi\pi$), would need complicated joint distribution in the likelihood.

Use instead approximate relation between any 2 invariant masses obtained with 2 arbitrary mass assignment to the tracks (if $m \ll p$):

2-body invariant mass with \overline{m}_1 and \overline{m}_2 mass assignments

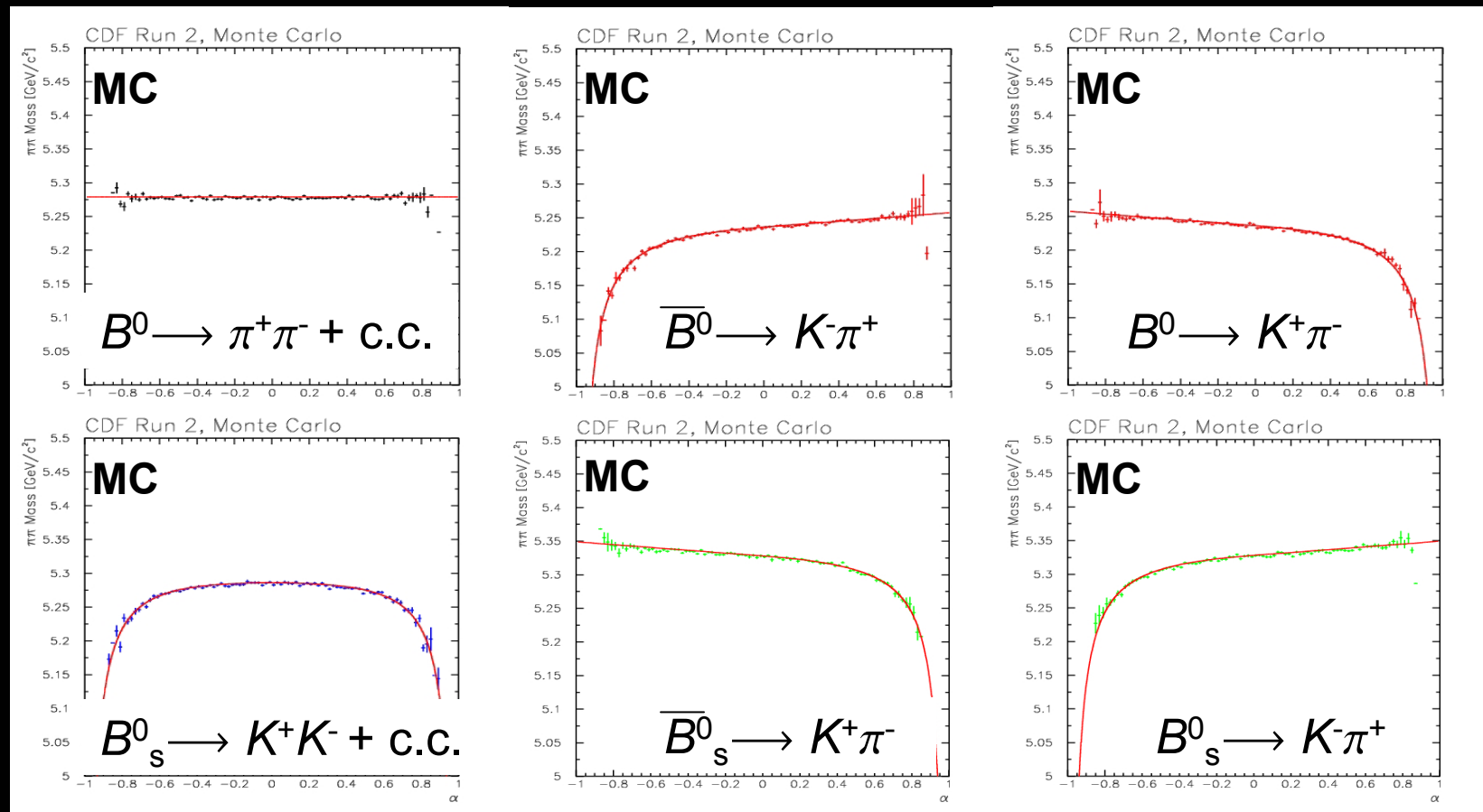
$$M_{m_1, m_2}^2 \approx M_{\overline{m}_1, \overline{m}_2}^2 + \left(1 + \frac{p_1}{p_2}\right) (m_2^2 - \overline{m}_2^2) + \left(1 + \frac{p_2}{p_1}\right) (m_1^2 - \overline{m}_1^2)$$

2-body invariant mass with m_1 and m_2 mass assignments

Information condensed in just 2 observables: a single candidate invariant mass and ratio of momenta: looser correlation and easier to handle

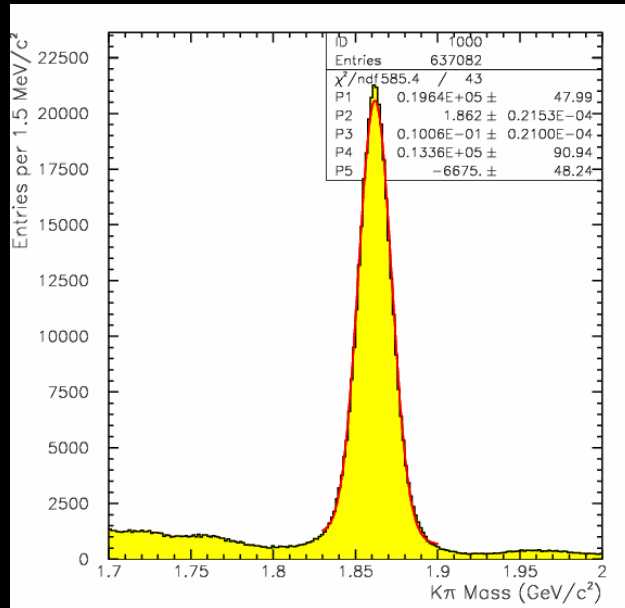
Peak composition handle 1: kinematics

$\pi\pi$ -mass vs signed momentum imbalance: $(1 - p_{\min}/p_{\max})q_{\min}$



discriminates among modes (and among flavors in $K\pi$ modes).

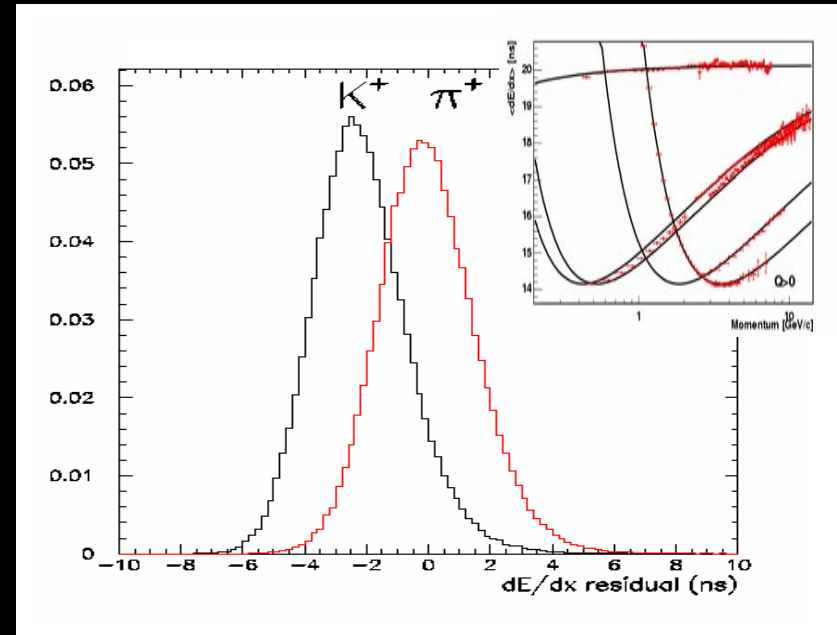
Peak composition handle 2: dE/dx



~95% pure K and π samples from
~300,000 decays:

$$D^{*+} \longrightarrow D^0 \pi^+ \longrightarrow [K^- \pi^+] \pi^+$$

Strong D^{*+} decay tags the D^0
flavor. dE/dx accurately calibrated
over tracking volume and time.



1.4σ K/π separation at $p > 2$ GeV
(\equiv 60% of “perfect” separation)

~11% residual correlation from
gain/baseline common fluctuations
included in the fit of composition

Fit of composition

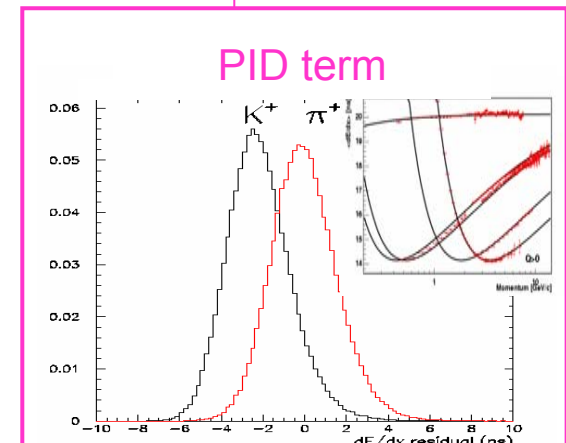
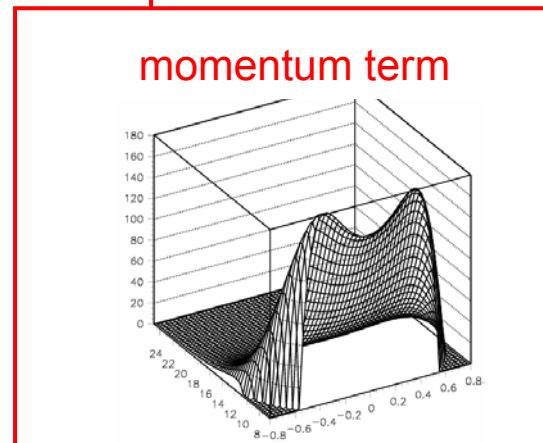
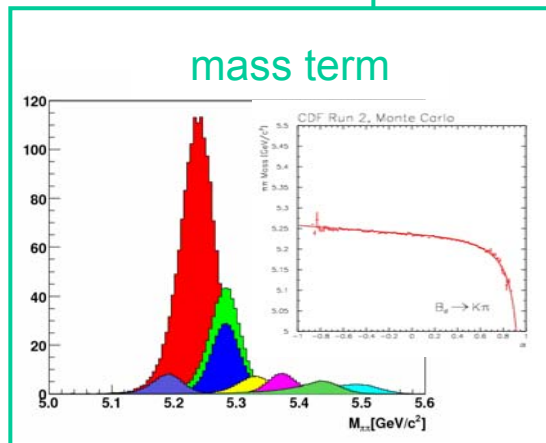
Un-binned ML fit that uses kinematic and PID information from 5 observables

$$\mathcal{L}(\vec{\theta}) = \prod_{i=1}^N \mathcal{L}_i(\vec{\theta})$$

fraction of j^{th} mode, to be determined by the fit

$$\mathcal{L}_i(\vec{\theta}) = (1 - b) \sum f_j \mathcal{L}_j^{\text{sign}} + b \mathcal{L}^{\text{bckg}}$$

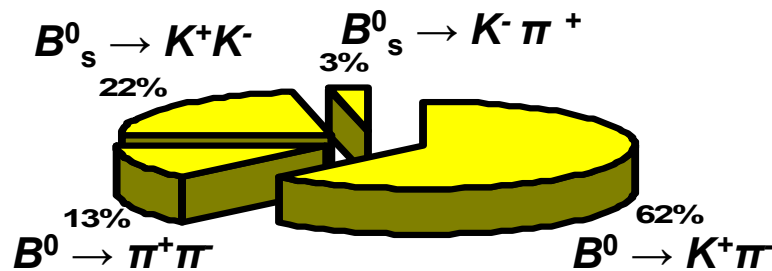
$$\mathcal{L} \sim \underbrace{\varphi^m(m_{\pi\pi}|\alpha)}_{\text{mass term}} \times \underbrace{\varphi^p(\alpha, p_{\text{tot}})}_{\text{momentum term}} \times \underbrace{\varphi^{\text{PID}}(dE/dx_1, dE/dx_2|\alpha, p_{\text{tot}})}_{\text{PID term}}$$



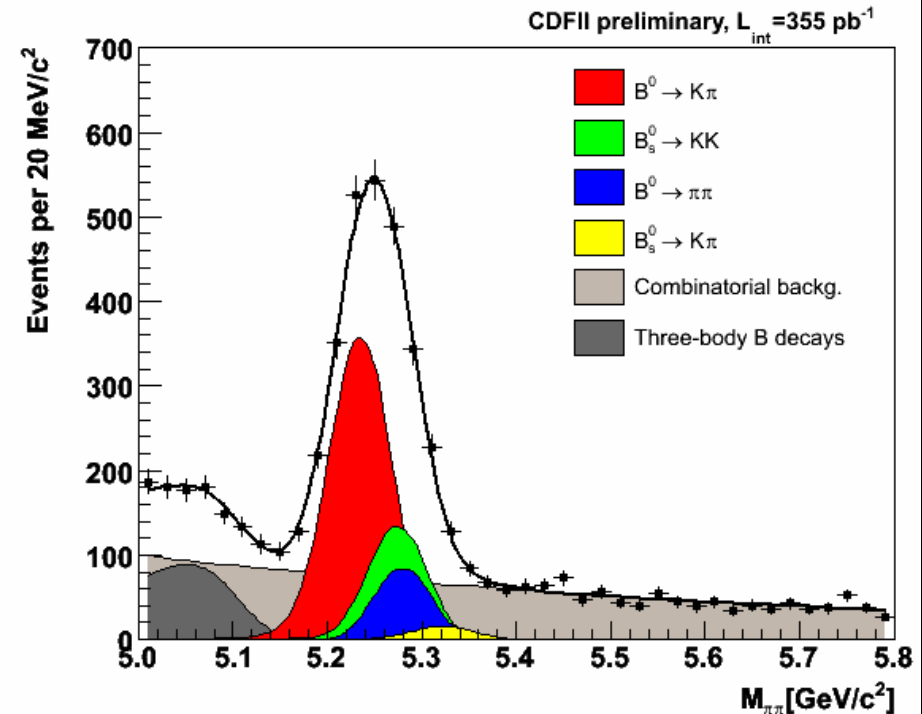
Signal shapes: from MC and analytic formula
Background shapes: from data sidebands

sign and bckg shapes
from $D^0 \rightarrow K\pi^+$

Uncorrected fit results



mode	fraction [%]	yield
$B^0 \rightarrow \pi^+ \pi^- + \bar{B}^0 \rightarrow \pi^+ \pi^-$	13.2 ± 1.4	313 ± 34
$B_s^0 \rightarrow K^- \pi^+ + \bar{B}_s^0 \rightarrow K^+ \pi^-$	2.7 ± 1.3	64 ± 30
$B_s^0 \rightarrow K^+ K^- + \bar{B}_s^0 \rightarrow K^+ K^-$	22.0 ± 1.6	523 ± 41
$B^0 \rightarrow K^+ \pi^- + \bar{B}^0 \rightarrow K^- \pi^+$	62.1 ± 1.7	1475 ± 60
$B^0 \rightarrow K^+ \pi^-$	—	787 ± 42
$\bar{B}^0 \rightarrow K^- \pi^+$	—	689 ± 41



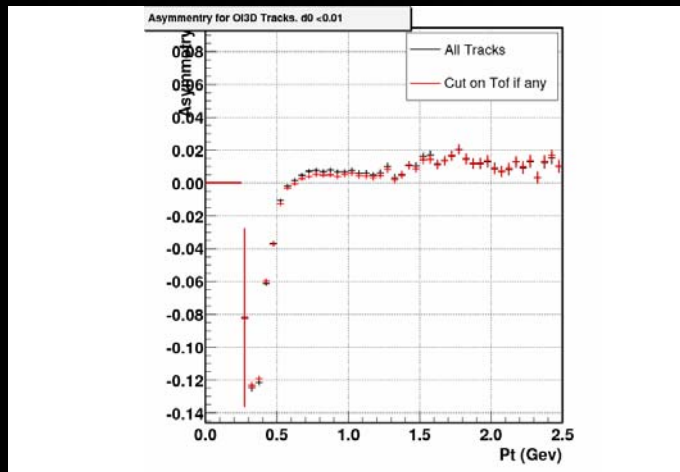
$$A_{\text{CP}} \Big|_{\text{RAW}} = \frac{N_{\text{raw}}(\bar{B}^0 \rightarrow K^- \pi^+) - N_{\text{raw}}(B^0 \rightarrow K^+ \pi^-)}{N_{\text{raw}}(\bar{B}^0 \rightarrow K^- \pi^+) + N_{\text{raw}}(B^0 \rightarrow K^+ \pi^-)} = -0.066 \pm 0.039$$

Correct the fit result for trigger, acceptance, and selection efficiency to convert it into a measurement

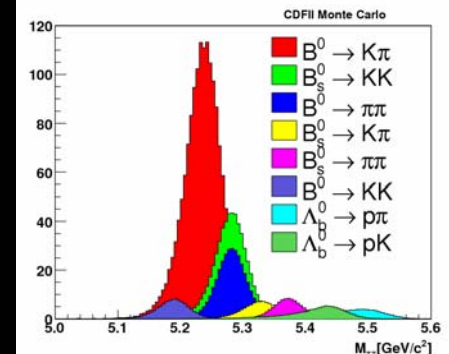
Extraction of asymmetry

$$A_{CP} = \frac{N(\bar{B}^0 \rightarrow K^- \pi^+) \Big|_{\text{raw}} \frac{\epsilon_{kin}(B^0 \rightarrow K^+ \pi^-)}{\epsilon_{kin}(\bar{B}^0 \rightarrow K^- \pi^+)} - N(B^0 \rightarrow K^+ \pi^-) \Big|_{\text{raw}}}{N(\bar{B}^0 \rightarrow K^- \pi^+) \Big|_{\text{raw}} \frac{\epsilon_{kin}(B^0 \rightarrow K^+ \pi^-)}{\epsilon_{kin}(\bar{B}^0 \rightarrow K^- \pi^+)} + N(B^0 \rightarrow K^+ \pi^-) \Big|_{\text{raw}}}$$

A < 2% charge asymmetry affects the CDFII detector and tracking code.

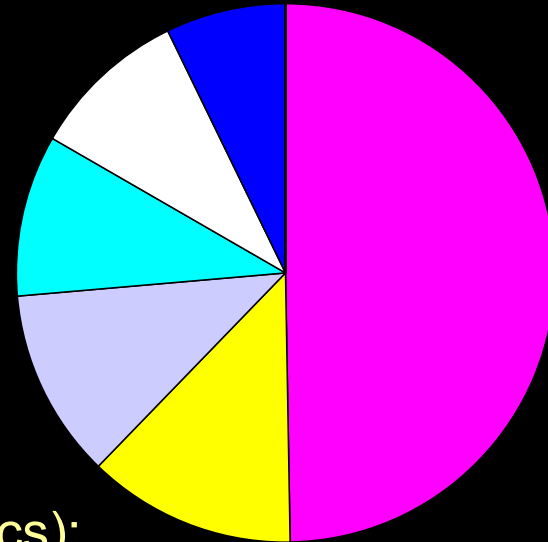


Only the different K^+/K^- nuclear interaction rate with the tracker material matters. Effect is under control down to 0.5% in CDF paper on $A_{CP}(D^0 \rightarrow h^+ h')$. We used the same procedure to extract the ratio of efficiencies. ~ 1% correction



Dominant systematic uncertainties

Total systematic uncertainty is 0.7% , much smaller than the 3.9% statistical uncertainty.



- dE/dx model (partially reduces with statistics);
- nominal *B*-meson masses input to the fit (reduces with statistics);
- mass-resolution model;
- global scale of masses;
- charge-asymmetries in background;
- combinatorial background model.

Asymmetry Result

$$A_{\text{CP}}^{\text{CDF}}(B^0 \rightarrow K^+ \pi^-) = -0.058 \pm 0.039 \text{ (stat.)} \pm 0.007 \text{ (syst.)}$$

$A_{\text{CP}} \sim 1.5\sigma$ different from 0, and compatible with B -factories results:

$$A_{\text{CP}}^{\text{Belle}}(B^0 \rightarrow K^+ \pi^-) = -0.113 \pm 0.022 \text{ (stat.)} \pm 0.008 \text{ (syst.)} \quad A_{\text{CP}}^{\text{Babar}}(B^0 \rightarrow K^+ \pi^-) = -0.133 \pm 0.030 \text{ (stat.)} \pm 0.009 \text{ (syst.)}$$

B -factories statistical uncertainty is just ~20% better with same sample size and systematic uncertainties are comparable.

With data already available on disk, we expect ~2.5% statistical uncertainty: CDF soon very competitive (summer).

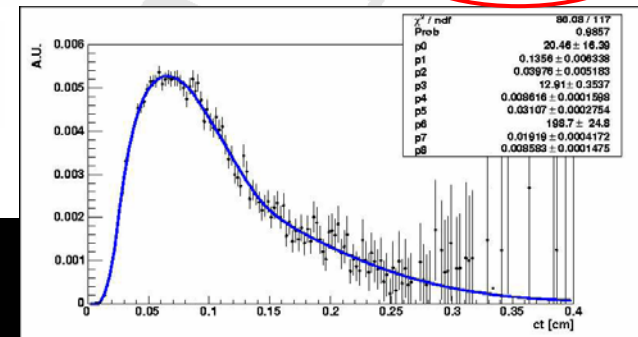
In same data, we expect first observation of $B_s^0 \rightarrow K^- \pi^+$ decay: will measure its BR and CP asymmetry that is expected large. NP-check proposed by Lipkin (Lipkin, Phys.Lett.B621:126, 2005).

$B^0_s \rightarrow K^+ K^-$ lifetime analysis

Add lifetime information to the fit of composition:

$$\mathcal{L} \sim \wp^m(m_{\pi\pi}|\alpha) \wp^p(\alpha, p_{\text{tot}}) \wp^{\text{PID}}(dE/dx_1, dE/dx_2|\alpha, p_{\text{tot}}) \wp^{\text{life}}(ct).$$

$$\wp^{\text{life}}(ct) = \underbrace{\exp(ct)}_{\text{decay}} \times \underbrace{\text{Gauss}(ct)}_{\text{detector smearing}} \times \underbrace{\varepsilon(ct)}_{\text{trigger bias}}$$



Trigger bias for signal is extracted from detailed simulation.

Procedure validated in unbiased $B \rightarrow J/\psi X$ decays from dimuon trigger.

Check that lifetime fits of samples with/without applying track-trigger cuts yield consistent results.

Lifetime p.d.f for background is extracted from higher mass data sideband.

$B_s^0 \rightarrow K^+ K^-$ lifetime results

	$c\tau(B^0) [\mu\text{m}]$	$c\tau(B_s^0 \rightarrow K^+ K^-) [\mu\text{m}]$
both free	452 ± 24	463 ± 56
$c\tau(B^0)$ constrained to PDG	—	458 ± 53

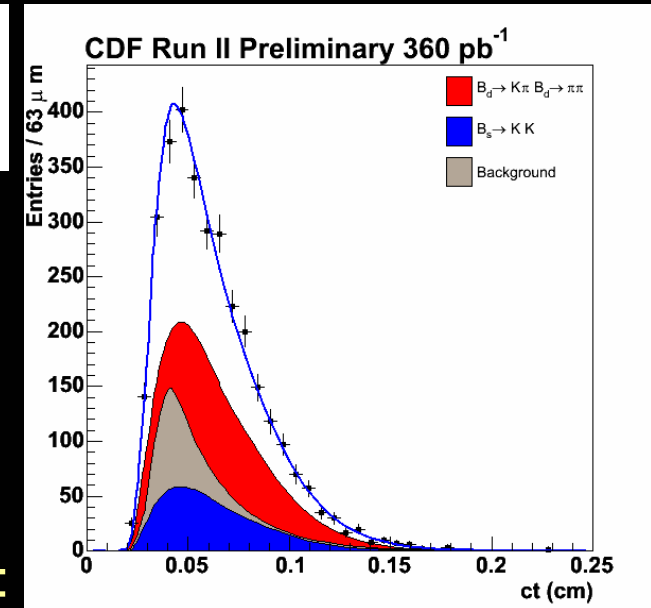
$B_s^0 \rightarrow K^+ K^-$ predicted ~95% CP-even: has the lifetime of “light B_s^0 ” :

$$\tau_L = 1.53 \pm 0.18 \text{ (stat.)} \pm 0.02 \text{ (syst.) ps}$$

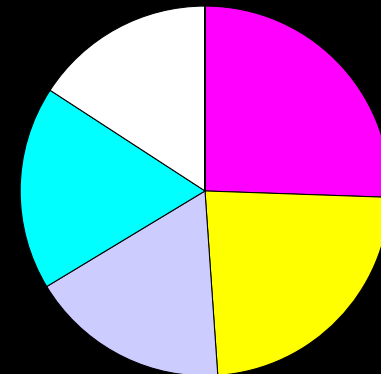
Combine with HFAG average $(\tau_L^2 + \tau_H^2)/(\tau_L + \tau_H)$:

$$\frac{\Delta\Gamma_s^{\text{CP}}}{\Gamma_s^{\text{CP}}} = -0.08 \pm 0.023 \text{ (stat.)} \pm 0.03 \text{ (syst.)}$$

- detector alignment;
- dE/dx model;
- input $p_T(B)$ in simulation;
- trigger-bias.
- lifetime model of background;



Dominant systematics :



Search for FCNC decays

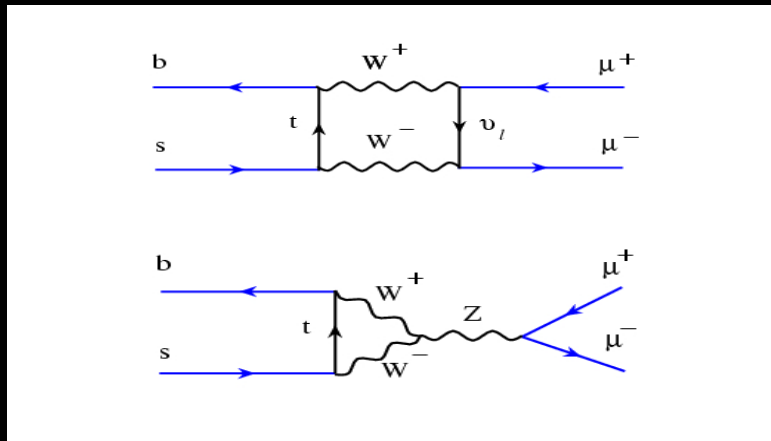
$$B^0 / B_s^0 \rightarrow \mu^+ \mu^-$$

Search for $B^0/B_s^0 \rightarrow \mu^+\mu^-$ decays

STANDARD MODEL

FCNC strongly suppressed.
expected $\text{BR}(B_s^0 \rightarrow \mu^+\mu^-) \sim 10^{-9}$:
a factor ~ 100 below CDF reach.

$B^0 \rightarrow \mu^+\mu^-$ further suppressed by
factor $|V_{td}/V_{ts}|^2$

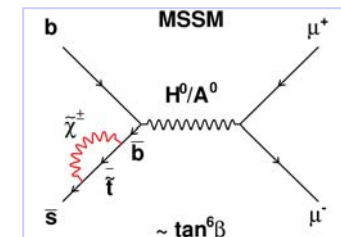


SUSY

NP contributions enhance BR by few
orders of magnitude, allowing
observation at the Tevatron.

MSSM: $\text{BR} \sim (\tan\beta)^6$: 100 times larger

RPV: tree diagram allowed



Only CDF can observe both B_s^0 and B^0 and distinguish between them

Search for $B^0/B_s^0 \rightarrow \mu^+\mu^-$ decays

Search in sample from “rare” di-muon trigger:

Use a Likelihood-Ratio discriminant to distinguish signal from background

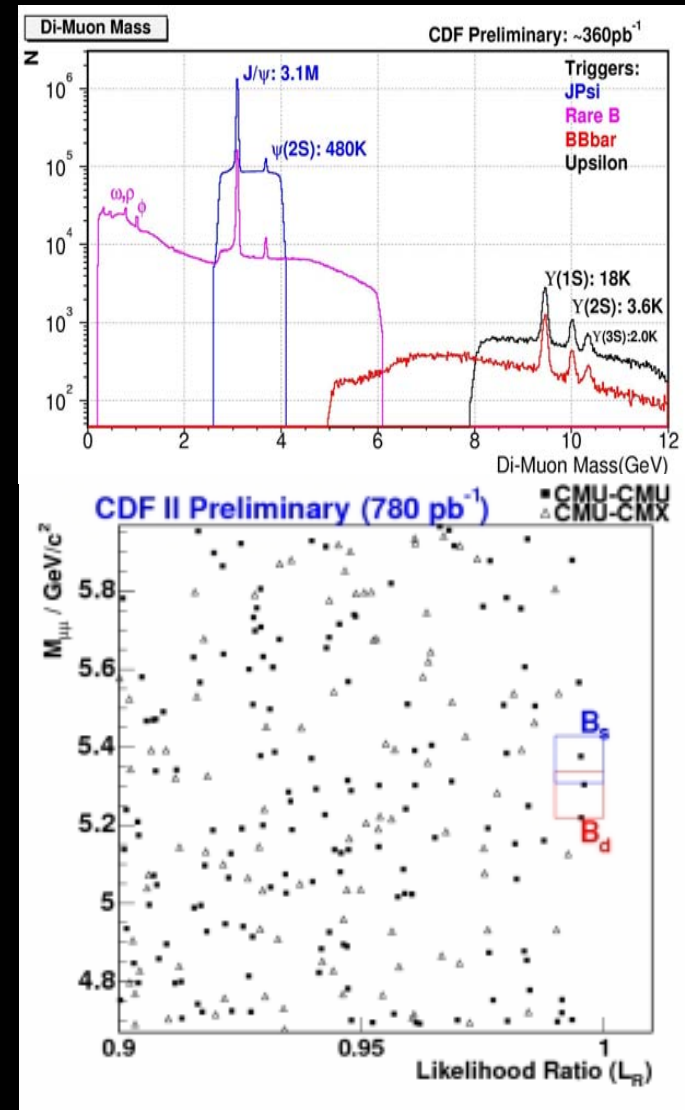
LR uses: (a) decay-length, (b) isolation of the B , (c) 3D-pointing of the B to the $\bar{p}p$ vertex

Understand the background in search window, and measure BR (or set limit) with respect to normalization $B^+ \rightarrow J/\psi K^+$ mode.

No signal found, world best upper limits set:

$$\text{BR}(B_s^0 \rightarrow \mu^+\mu^-) < 8 \times 10^{-8} \text{ @ 90\% CL}$$

$$\text{BR}(B^0 \rightarrow \mu^+\mu^-) < 2.3 \times 10^{-8} \text{ @ 90\% CL}$$



Summary

As data keep flowing, CDF impact on FP becomes more and more crucial: Charm-less two-body B decays, a case-study that shows how CDF is competitive with (B^0) and complementary to (B_s^0) B -factories.

- direct CPV in $B^0 \rightarrow K^- \pi^+$, small systematics, and as yet available statistics places CDF among the best by this summer.
- Unique opportunity to combine with $B_s^0 \rightarrow K^- \pi^+$ decays.
- Unique extraction of $\Delta\Gamma_s/\Gamma_s$ in $B_s^0 \rightarrow K^- K^+$ (already one of world best results)
- Unique simultaneous sensitivity to $B^0/B_s^0 \rightarrow \mu^+ \mu^-$ (already world best results)



Latest results on B_s^0 mixing
Jónatan Piedra, today at 17.00



Quantum numbers of X(3872)
Ilya Kravchenko, tomorrow at 11.00



$\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ lifetime
Jónatan Piedra, today at 17.00



World best B_c^+ mass
Ilya Kravchenko, tomorrow at 11.00



b -hadron production fractions
Ilya Kravchenko, tomorrow at 11.00



World best B_c^+ lifetime
Ilya Kravchenko, tomorrow at 11.00

ADDITIONAL MATERIAL